

# Weak Boson Emission in Hadron Collider Processes

all results are preliminary

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# 1 – Introduction

- In the past few years calculations of electroweak (EW) radiative corrections at high energies ( $\gg M_{W,Z}$ ) have been performed for a number of processes
  - ➡  $f' \bar{f} \rightarrow \ell' \ell$  (Kühn et al.)
  - ➡  $p \bar{p}^{(-)} \rightarrow \ell^\pm \nu, p \bar{p}^{(-)} \rightarrow \ell^+ \ell^-$  (UB, D. Wackeroth, Dittmaier and Krämer)
  - ➡ isolated photon and  $Zj$  production at hadron colliders (Kühn et al.)
  - ➡ di-boson production (Accomando et al., Hollik and Meier)
  - ➡ inclusive jet production at hadron colliders (Nolten et al.)
  - ➡  $p \bar{p}^{(-)} \rightarrow t \bar{t}$  (Nolten et al., Kühn et al.)
  - ➡ single top production (Comelli et al., Beccaria et al.)

- These calculations show that EW corrections become **large and negative** at high energies, due to the presence of **Sudakov-like logarithms**  $((\alpha/\pi) \log(\hat{s}/M_{W,Z}^2))$ .
- **Where are these logarithms coming from?**
  - ☞ In QED, these logarithms cancel between virtual and real corrections (**KLN theorem**); observables which are inclusive over soft final states (ie. photons) are infrared safe (**Bloch-Nordsieck (BN) theorem**)
  - ☞ In the EW case, the incoming  $q'\bar{q}$  system does have a non-zero  $SU(2) \times U(1)$  charge, and, due to the non-abelian character of the gauge group, the BN-theorem is violated (**remark**: In QCD the BN-theorem is also violated, but one sums/averages over colors. This effectively restores the BN-theorem (**Bodwin, Brodsky, Lepage**))

- ☞ In the EW case, the  $W$  and  $Z$  masses act as infrared regulators, and the virtual weak corrections are finite. **There is no technical reason to take into account real emission diagrams.**
- ☞ Furthermore, since the EW symmetry is broken and the massive  $W$  and  $Z$  bosons decay, the real EW radiative corrections (ie.  $W$  and  $Z$  radiation) lead to a different final state.
- Therefore, contributions from weak boson emission usually are not taken into account when calculating electroweak radiative corrections.
- This is ok if one considers **exclusive** final states.
- However, in experiment, analyses usually involve (semi-)inclusive final states.

- Real EW corrections ( $W$  and  $Z$  radiation) thus have to be included in the calculation.
- This results in a partial compensation of the large negative corrections originating from the Sudakov-like logarithms
- So, how large are EW radiative corrections when realistic experimental conditions are taken into account?
- I calculated weak boson emission effects for all processes for which the virtual weak corrections are known.
- In the following I discuss some interesting examples
- wherever possible consider cross section ratios: this minimizes cut, PDF and scale dependence

## 2 – Isolated Photon Production

- LO process:  $p\bar{p}^{(-)} \rightarrow \gamma j$
- typical CDF/DØ selection criteria:
  - ☞ require a hard ( $p_T(\gamma) > 10$  GeV), isolated ( $\Delta R > 0.4$ ) photon
  - ☞ some analyses also require the missing  $E_T$  in the event to be small ( $\cancel{p}_T < 20$  GeV) to reject events with large calorimeter noise
  - ☞ there is no restriction on the number of jets or leptons in the event
- The one-loop NLL  $\mathcal{O}(\alpha_s\alpha^2)$  weak corrections have a very compact form and can easily be included in a  $\gamma j$  parton level MC program (Kühn et al.)  
they agree at the percent level with the full weak one-loop corrections

- Real EW  $\mathcal{O}(\alpha_s \alpha^2)$  radiative corrections:  $W\gamma j$  and  $Z\gamma j$  production

☞ Don't care about the jet in  $V\gamma j$  ( $V = W, Z$ ): it can be soft.

☞ Should include  $V\gamma$  production

☞ better strategy: include  $V\gamma$  production at NLO QCD (well known for more than a decade)

- Cuts (only on the photon!)

$$p_T(\gamma) > 25 \text{ (50) GeV} \quad \text{at Tevatron (LHC),}$$

$$|\eta(\gamma)| < 2.5 \quad \Delta R(\gamma, X) > 0.4$$

$$X = j, \ell$$

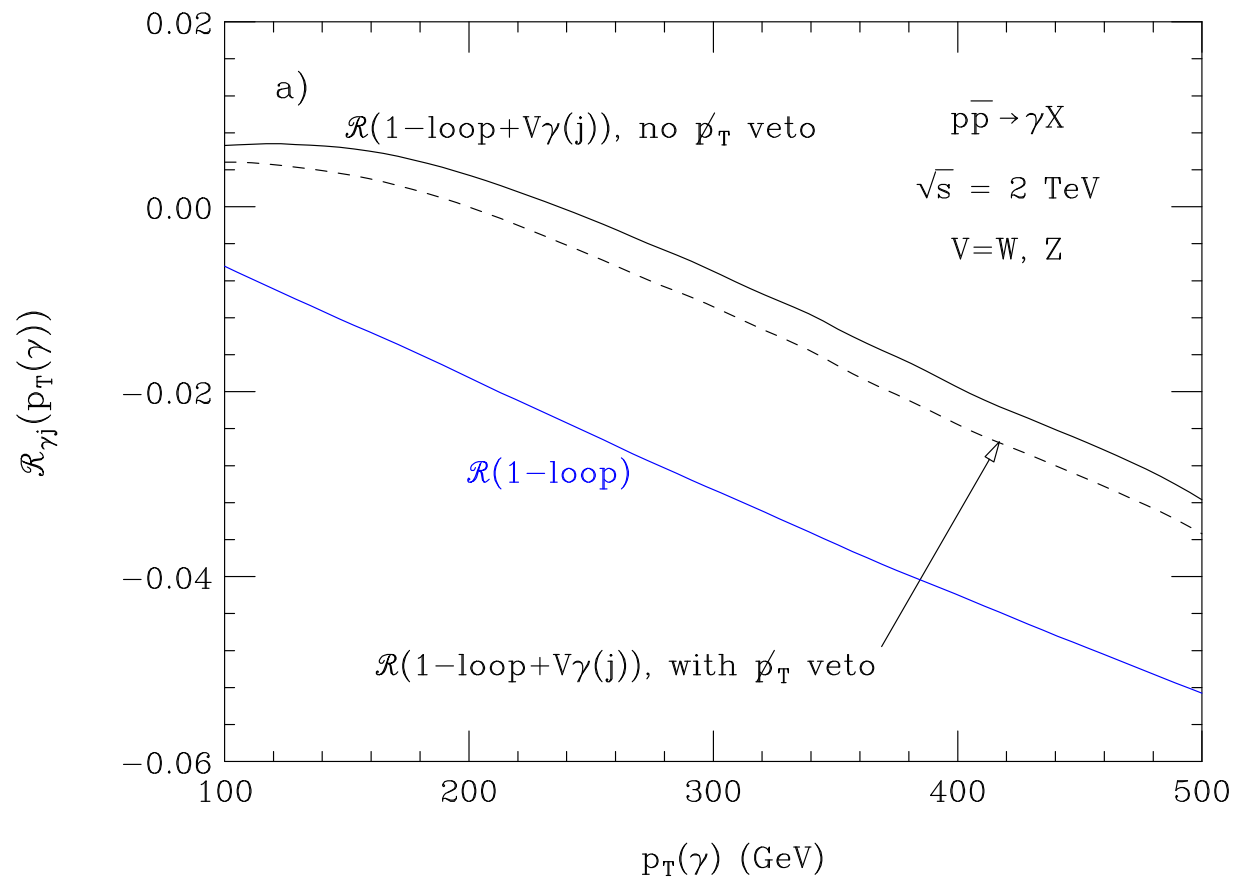
- Sometimes one also imposes a  $\cancel{p}_T$  veto: require

$$\cancel{p}_T < 5 \text{ GeV}^{1/2} \sqrt{\sum p_T}$$

- consider relative correction w/r to LO cross section:

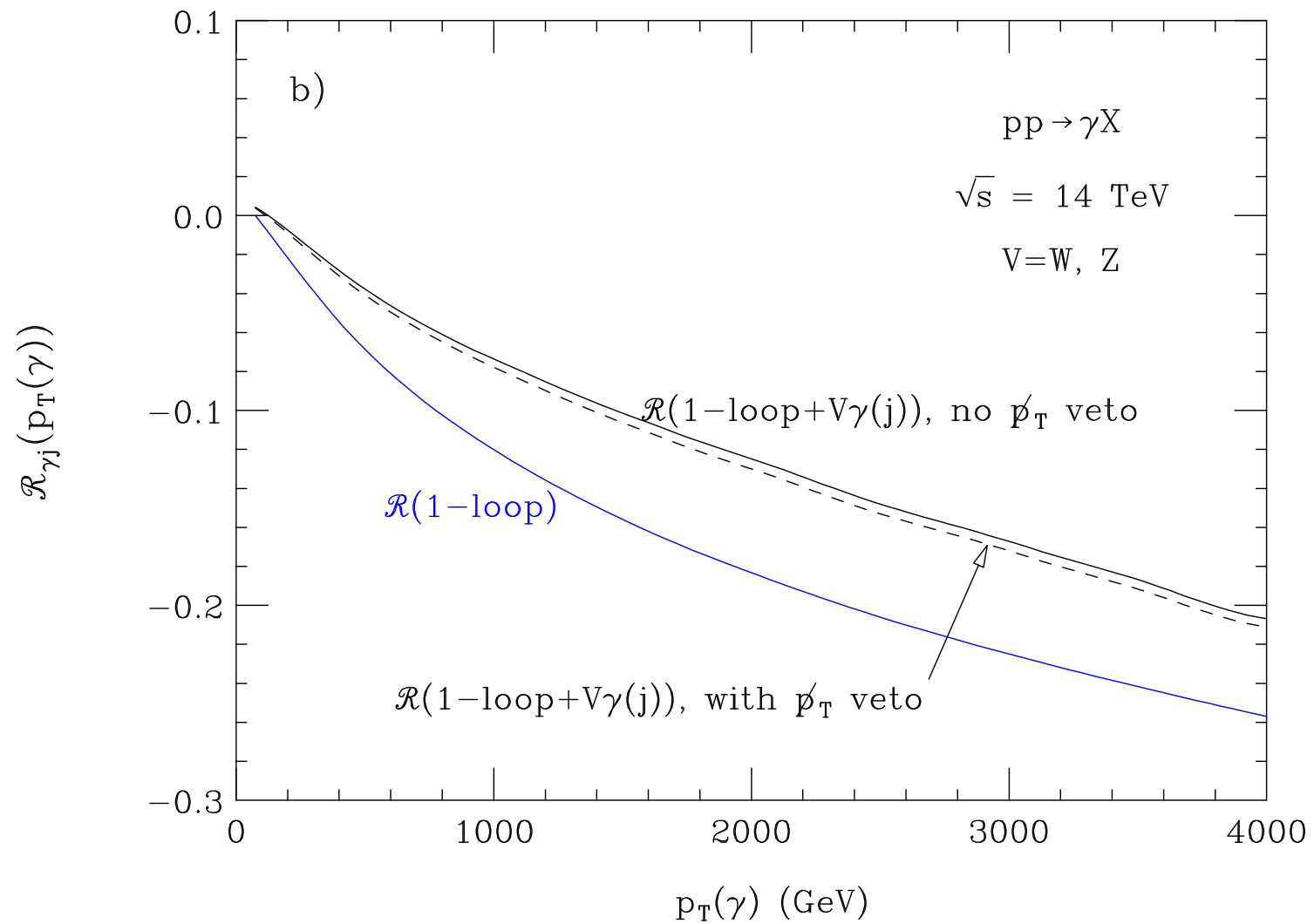
$$\mathcal{R}_Y(X) = \frac{d\sigma/dX}{d\sigma^{LO}(Y)/dX} - 1$$

with  $Y = \gamma j$ ,  $X = p_T(\gamma)$ . Tevatron:





... and LHC:



- There are large logarithms present in  $V\gamma j$  production:

$$d\hat{\sigma}(q_1 g \rightarrow V\gamma q_{1,2}) = d\hat{\sigma}(q_1 g \rightarrow \gamma q_1) \frac{\alpha}{4\pi \sin^2 \theta_W} \log^2 \left( \frac{p_T^2(\gamma)}{M_V^2} \right)$$

- there are no large logarithms in  $V\gamma$  production:  
it contributes significantly only for  $p_T(\gamma) < 200$  GeV
- the one-loop EW corrections are a few percent at most at the Tevatron  
weak boson emission considerably reduces the effect of the virtual weak corrections
- At the LHC one can measure the  $p_T(\gamma)$  distribution out to 1.5 TeV with  $10 \text{ fb}^{-1}$ :
  - ➡ without weak boson emission:  $\mathcal{R}_{\gamma j} = -0.15$
  - ➡ including weak boson emission:  $\mathcal{R}_{\gamma j} = -0.11$
  - ➡ moderate reduction

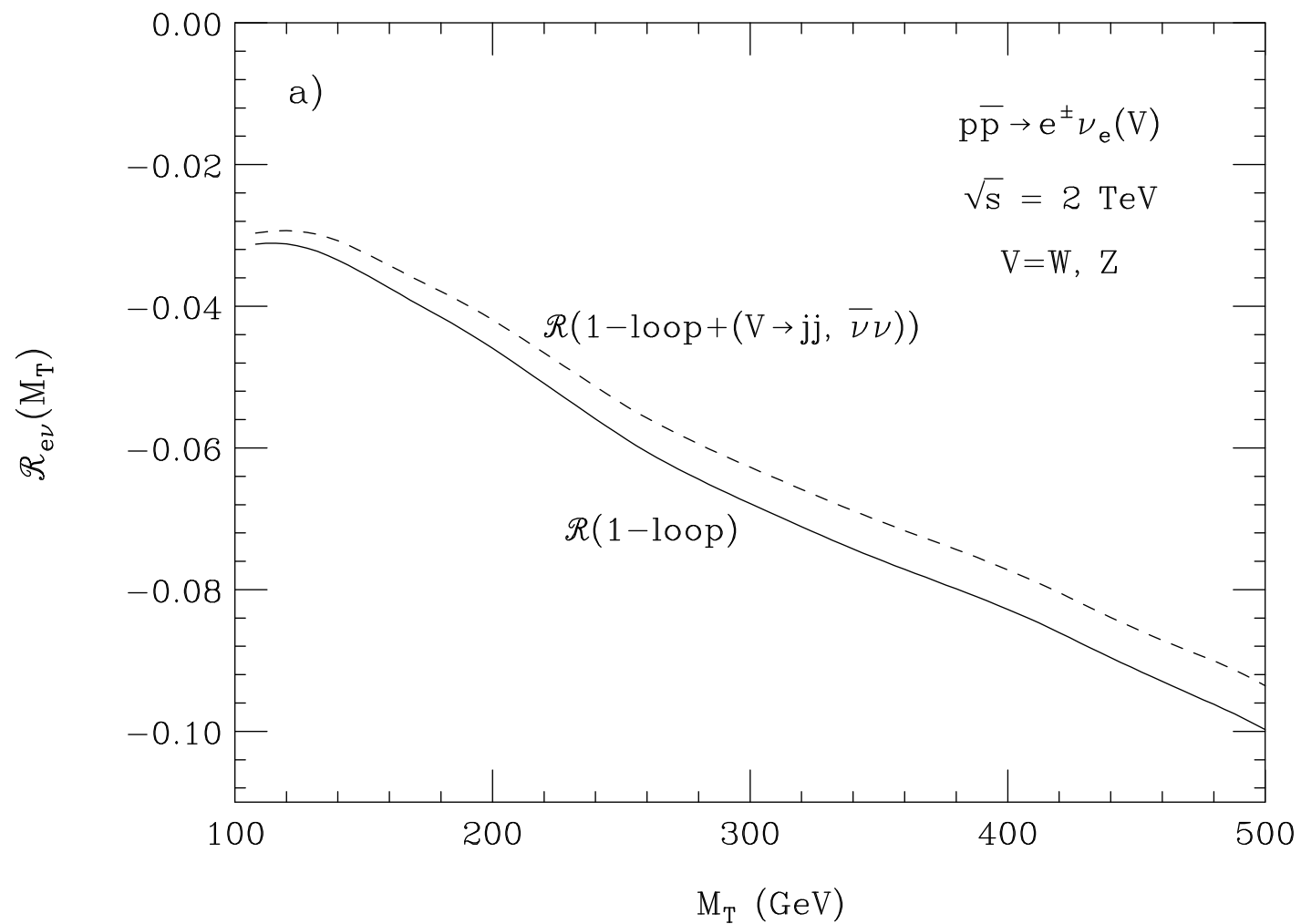
- weak boson emission effects are of the same size as the leading two-loop electroweak corrections (Kühn et al.)
- are the combined real + virtual weak corrections important?
  - ➡ compare with statistical and systematic uncertainties
  - ➡ Tevatron: systematic uncertainties dominate over statistical, except for the highest values of  $p_T(\gamma)$  one can access
  - ➡ Tevatron: systematic uncertainties are 10 – 20%
  - ➡ expect similar uncertainties at the LHC
  - ➡ real + virtual EW corrections are important at the LHC, but probably not at the Tevatron

### 3 – Charged Drell-Yan Production

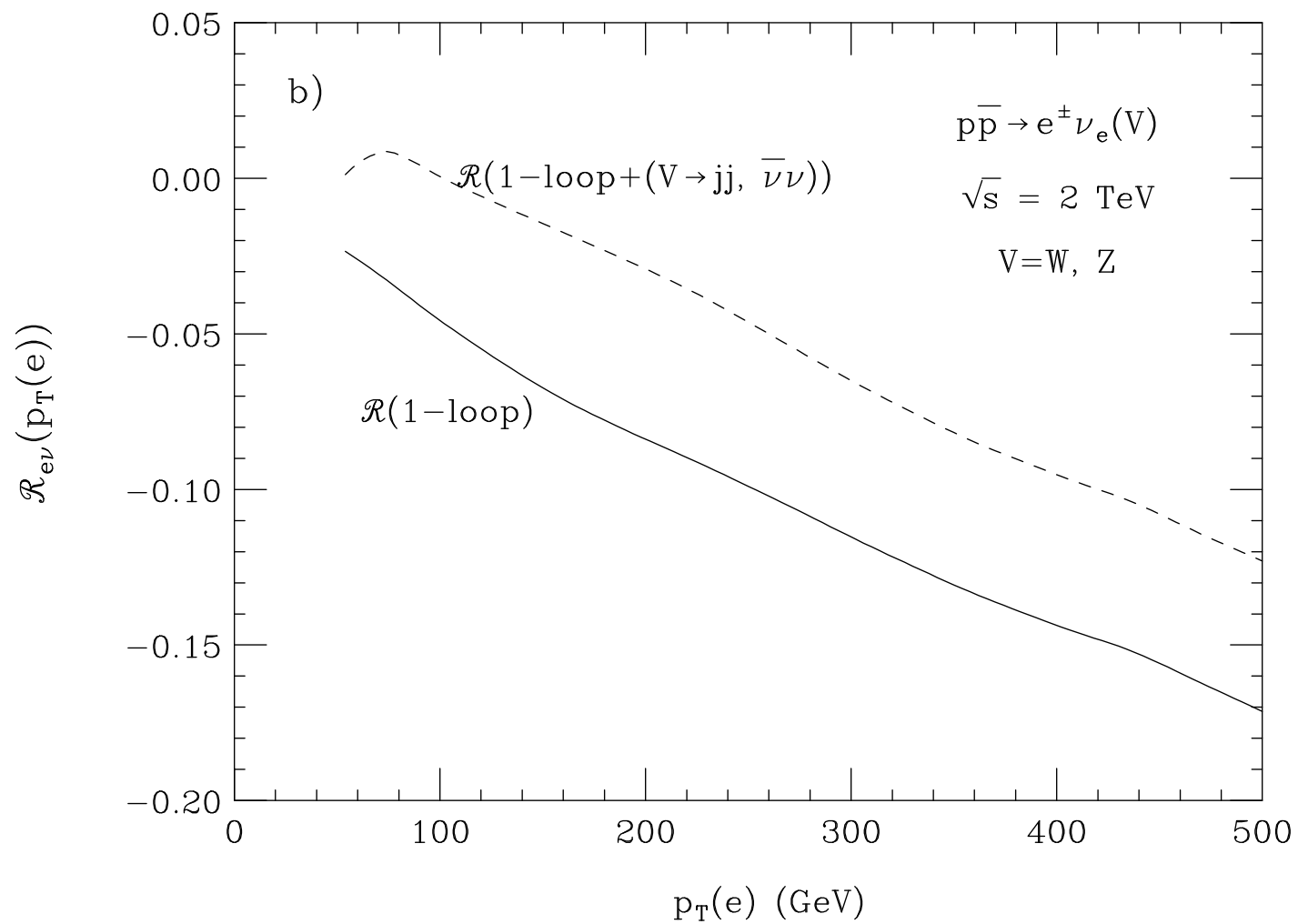
- LO:  $p\bar{p}^{(-)} \rightarrow \ell\nu$
- used to search for new heavy charged vector bosons
- selection criteria:
  - ➡ **one** high  $p_T$  charged lepton ( $p_T(\ell) > 25 \text{ GeV}$ ): events with two or more charged leptons are classified as di-boson events
  - ➡ missing transverse momentum  $\cancel{p}_T > 25 \text{ GeV}$
  - ➡ any number of jets
- real EW radiative corrections:  $W^\pm \ell \nu$  and  $Z \ell \nu$  production ( $WW$ ,  $WZ$  production, and  $W$ ,  $Z$  bremsstrahlung diagrams)

- virtual corrections: full one-loop  $\mathcal{O}(\alpha)$  (including photonic corrections)
- focus on  $\ell = e$ ; recombine photons and electrons for small opening angles
  - ☞ necessary because photons and electrons which are collinear cannot be discriminated
  - ☞ minimizes the effect of the photonic corrections (we are not interested in them)
- for  $\mu$  final state relative effects are smaller because photonic corrections play a larger role (no recombination with photon; hard photons close to  $\mu$  are vetoed)
- consider  $e\nu$  transverse mass ( $M_T$ ) and  $p_T(e)$  distributions

## Tevatron: $M_T$ distribution



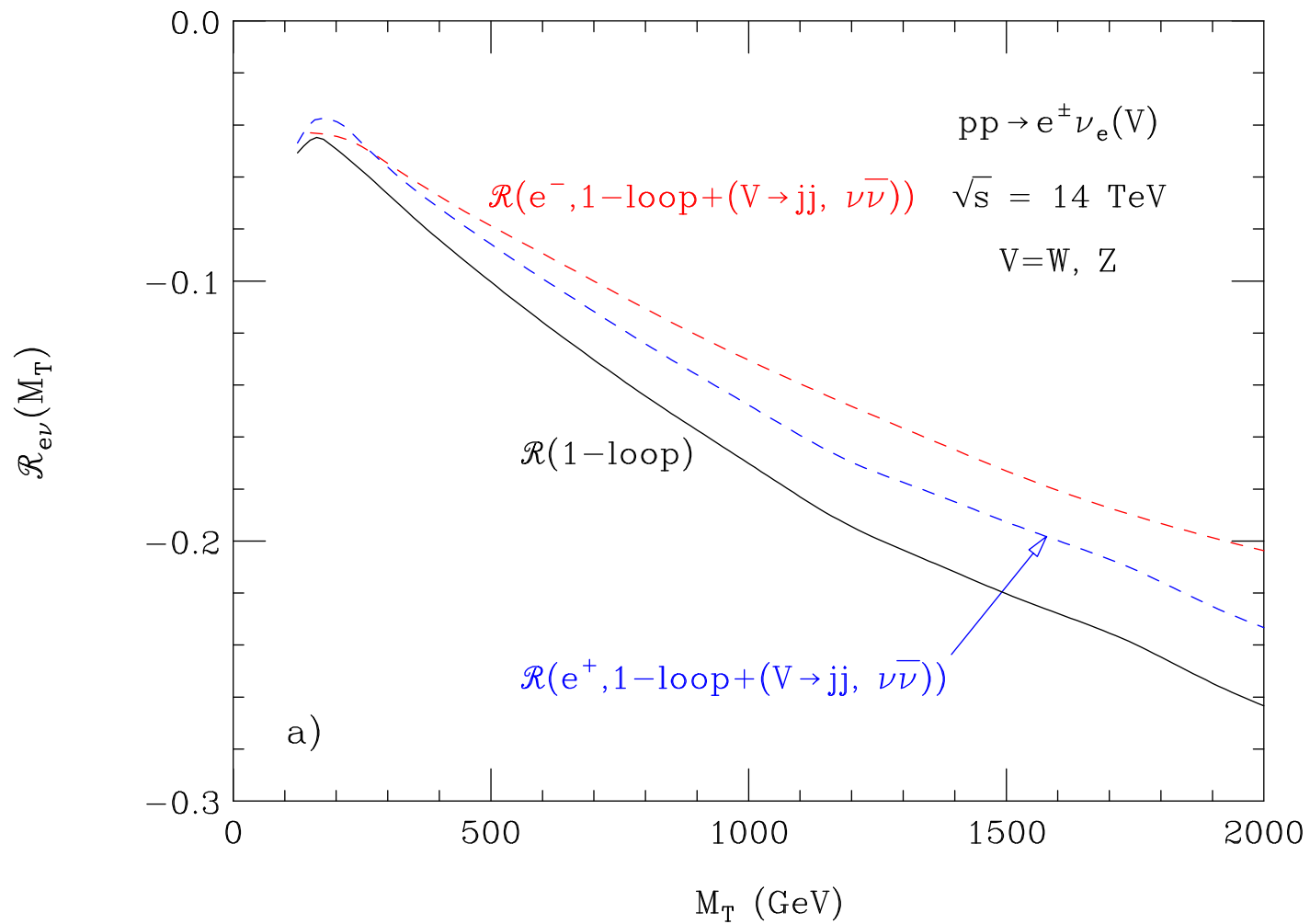
... and  $p_T(e)$  distribution

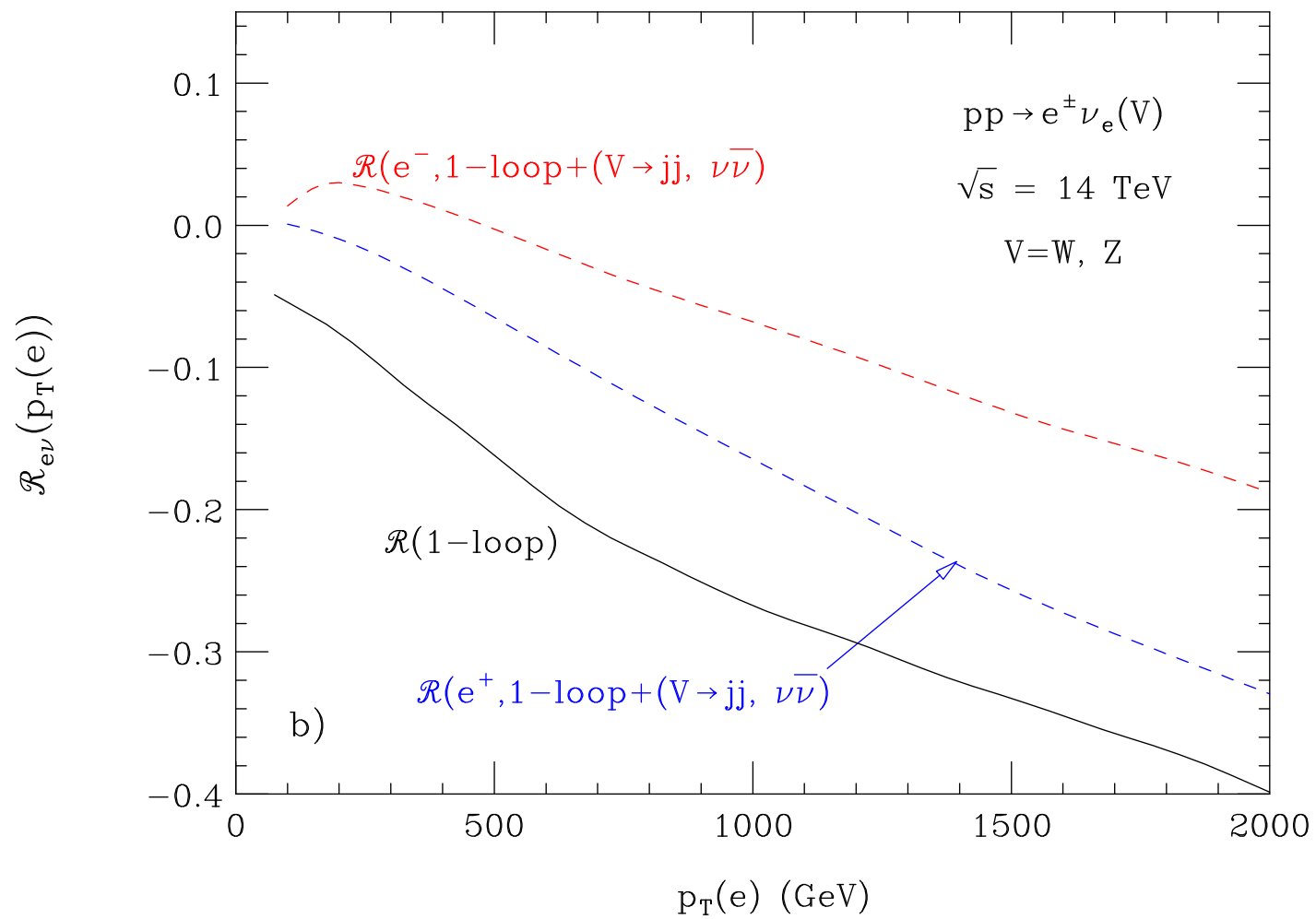


- virtual weak corrections become  $\mathcal{O}(10\%)$  at very large  $M_T$  or  $p_T$
- weak boson emission contribution small (about 1%) in the  $M_T$  distribution
- they are much larger (about 5%) in the  $p_T(e)$  distribution  
reason:  $e\nu$  necessarily off-shell in  $M_T$  distribution, but can be on-shell in  $p_T$  distribution



now the LHC...



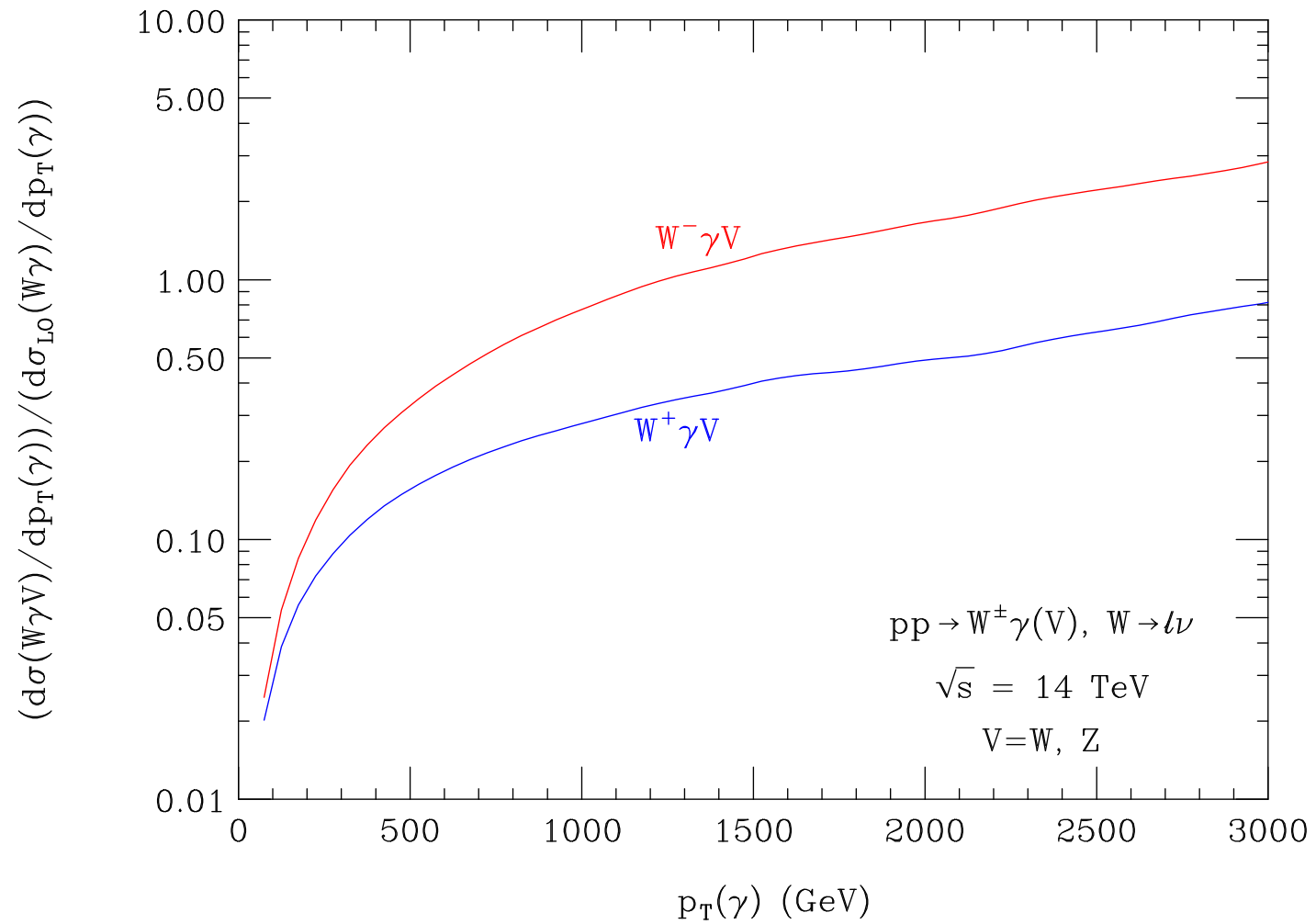


- At the LHC, the  $e^+\nu$  and  $e^-\nu$  cross sections are different ( $\sigma(e^+\nu) \gg \sigma(e^-\nu)$  at high energies)
- The virtual corrections are proportional to the Born amplitude  
→ relative corrections are equal for  $e^+\nu$  and  $e^-\nu$
- Since  $e\nu W$  production dominates the weak boson emission processes, the relative corrections for  $e^+\nu$  and  $e^-\nu$  are different
- Weak boson emission effects for  $e^-\nu$  are substantially larger
- Taking into account weak boson emission is clearly important

## 4 – $W\gamma$ and $Z\gamma$ Production

- physics interest: probing weak boson self-couplings
- virtual weak and photonic  $\mathcal{O}(\alpha)$  corrections have only been calculated for LHC
  - do not consider Tevatron case here
- event selection:
  - ☞ one (two) isolated charged lepton(s) with  $p_T(\ell) > 25 \text{ GeV}$  in  $W\gamma$  ( $Z\gamma$ ) case
  - ☞  $p_T > 25 \text{ GeV}$  for  $W\gamma$  production
  - ☞  $p_T$  veto in  $Z\gamma$  case:  $p_T < 5 \text{ GeV}^{1/2} \sqrt{\sum p_T}$
  - ☞ one hard, isolated photon:  $p_T(\gamma) > 50 \text{ GeV}$ ,  $\Delta R(\ell, \gamma) > 0.4$

- The high photon  $p_T$  cut essentially eliminates contributions from radiative  $W$  and  $Z$  decay
- weak boson emission processes:  $W\gamma V$  and  $Z\gamma V$  ( $V = W, Z$ ) production
- The SM LO  $W\gamma$  cross section is suppressed by a **radiation zero**:  
all helicity amplitudes vanish for  $\cos \theta^* = \pm 1/3$  where  $\theta^*$  is the parton CM scattering angle
- There is no radiation zero in  $pp \rightarrow W\gamma V$
- the  $W\gamma V$  to  $W\gamma$  cross section ratio for inclusive  $V$  decays can become quite large
- Since  $\sigma(WW\gamma) \gg \sigma(WZ\gamma)$  and  $\sigma(W^+\gamma) \gg \sigma(W^-\gamma)$  at high energies, the effect is more pronounced in the  $W^-\gamma$  channel



- comparison of cross section normalized to LO  $W\gamma$  rate,  $\delta$ , for virtual weak and photonic corrections and for weak boson emission (Accomando et al.)

$p_T(\gamma)$	$\delta(1\text{-loop})$	$\delta(W^+\gamma V)$	$\delta(W^-\gamma V)$
250 GeV	-7.2(1)%	8.9%	14.9%
450 GeV	-14.7(1)%	13.5%	28.3%
700 GeV	-21.8(1)%	21.6%	53.2%

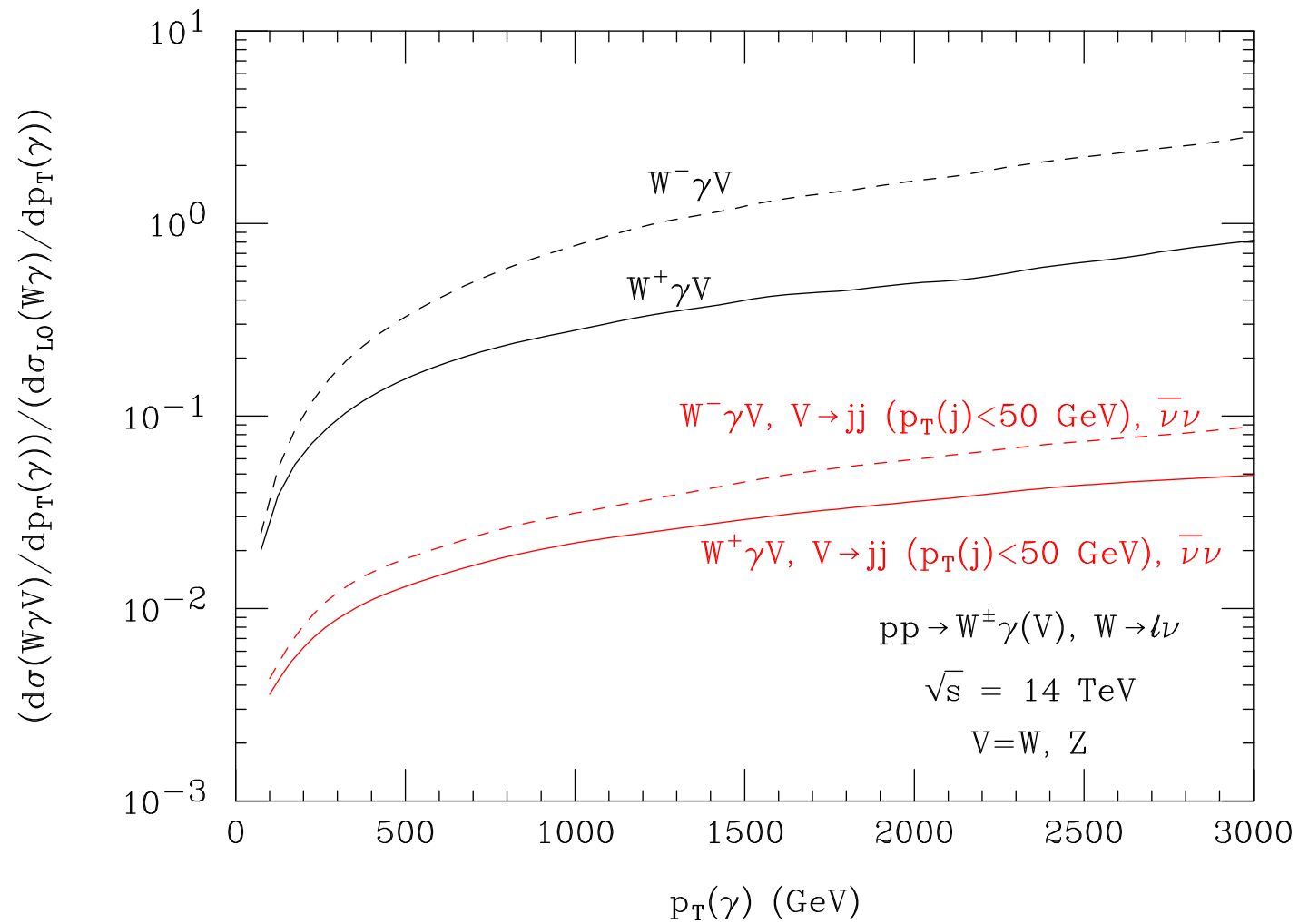
- ➡ in the  $W^+\gamma$  case, virtual and real corrections approximately cancel (accidental?)
- ➡ there is a **strong, positive** net effect in the  $W^-\gamma$  case

- Since LO  $W\gamma$  cross section is suppressed, the NLO QCD corrections to  $pp \rightarrow W\gamma$  become very large at high  $p_T$ :

$$d\hat{\sigma}(q_1 g \rightarrow V\gamma q_{1,2}) = d\hat{\sigma}(q_1 g \rightarrow \gamma q_1) \frac{\alpha}{4\pi \sin^2 \theta_W} \log^2 \left( \frac{p_T^2(\gamma)}{M_V^2} \right)$$

- At large  $p_T(\gamma)$ , the photon is usually balanced by a hard jet
- this obscures effects of anomalous  $WW\gamma$  couplings
- therefore: impose jet veto: no jets with  $p_T(j) > 50 \text{ GeV}$ ,  $|\eta(j)| < 2.5$  are allowed
- this reduces weak boson emission by more than a factor 10  
about one-half of the remaining effect is from  $WZ\gamma$  production with  $Z \rightarrow \bar{\nu}\nu$





- $Z\gamma$  production:

- ☞ there is **no** radiation zero

- ☞ the  $Z\gamma V$  to  $Z\gamma$  cross section ratio does not exceed  $\mathcal{O}(0.1)$

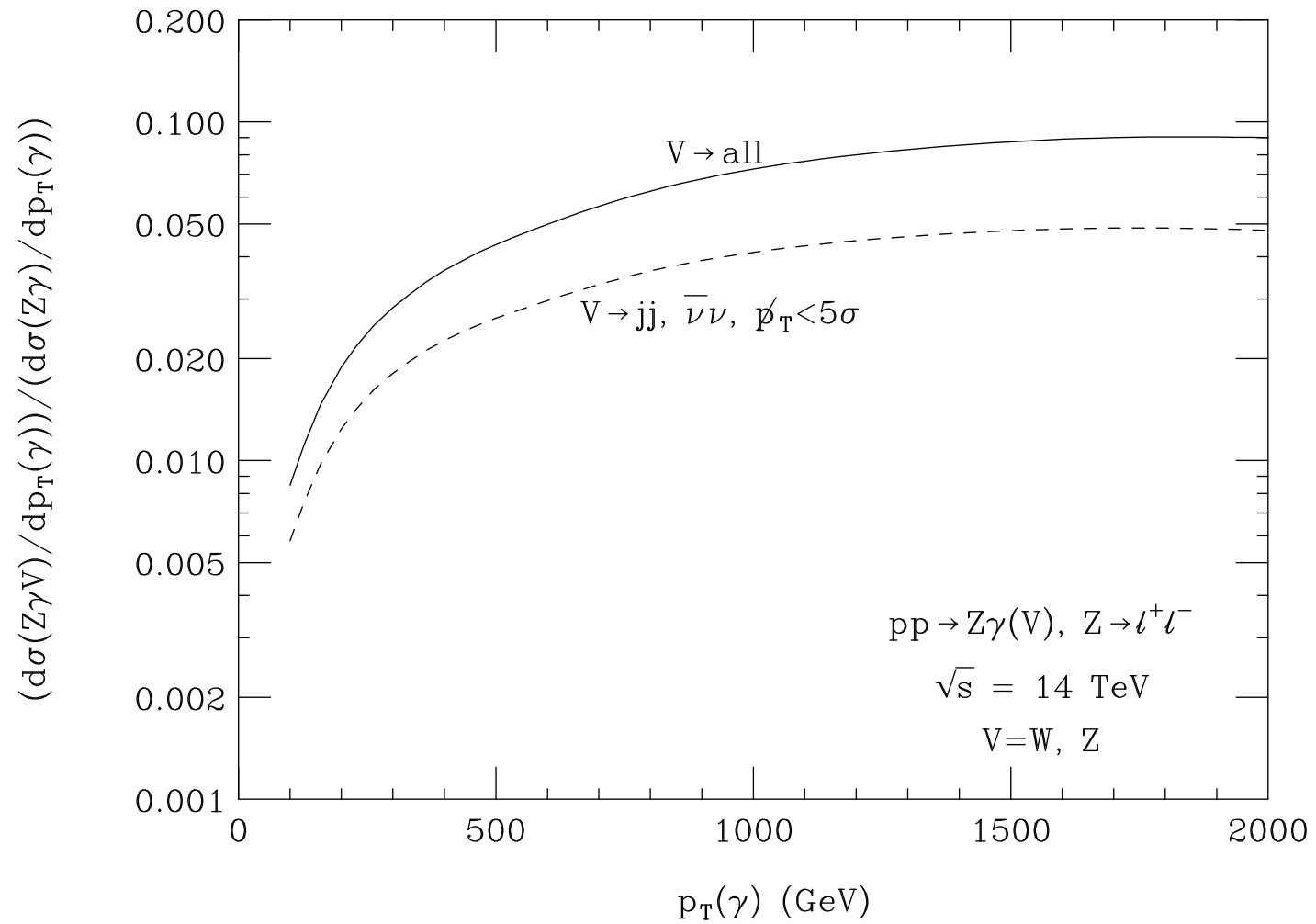
- ☞ QCD correction do not become large at high photon  $p_T$

- ☞ no need to impose a jet veto

- ☞ weak boson emission in  $Z\gamma$  production without a jet veto has about the same size as in  $pp \rightarrow W\gamma$  with a jet veto

- ☞  $p_T(\gamma) = 300 \text{ GeV}$ :  $\delta(1 - \text{loop}) = -0.15(1)$ ;  $\delta(Z\gamma V) = 0.02$

- $p_T(\gamma) = 500 \text{ GeV}$ :  $\delta(1 - \text{loop}) = -0.24(2)$ ;  $\delta(Z\gamma V) = 0.03$



## 5 – Single Top Production

- Differs substantially from previous cases
- focus on LHC
- $s$ -channel single top production:  $pp \rightarrow W^* \rightarrow t\bar{b}$ 
  - ➡ LO:  $\mathcal{O}(\alpha^2)$
  - ➡ weak boson emission processes:  $t\bar{b}W^-$  and  $t\bar{b}Z$  production
  - ➡  $t\bar{b}W^-$  production dominated by  $\mathcal{O}(\alpha_s^2)$   $t\bar{t}$  production! (Comelli, Ciafaloni)
  - ➡  $\sigma(t\bar{b}W) \gg \sigma(t\bar{b})$

- $t$ -channel single top production

- ☞ use  $b$ -quark PDF approach:  $u\bar{b} \rightarrow t\bar{d}$  etc.  $\mathcal{O}(\alpha^2)$

- ☞ require semileptonic top decay:  $pp \rightarrow tj \rightarrow \ell\nu bj$

- ☞ justified by selection cuts (CMS inspired)

- $p_T(\ell) > 20 \text{ GeV}$ ,  $|\eta(\ell)| < 2.5$

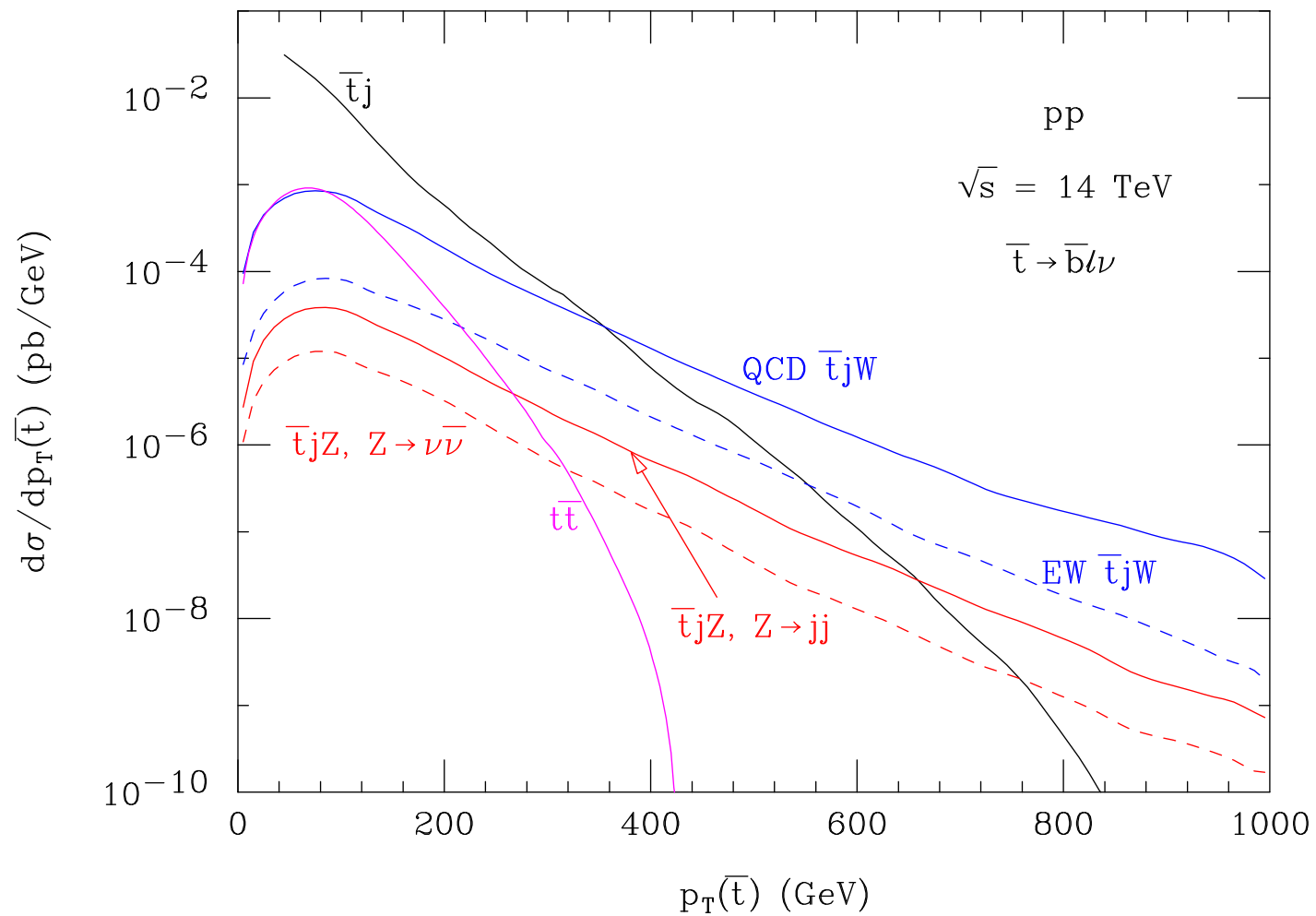
- $\cancel{p}_T > 40 \text{ GeV}$

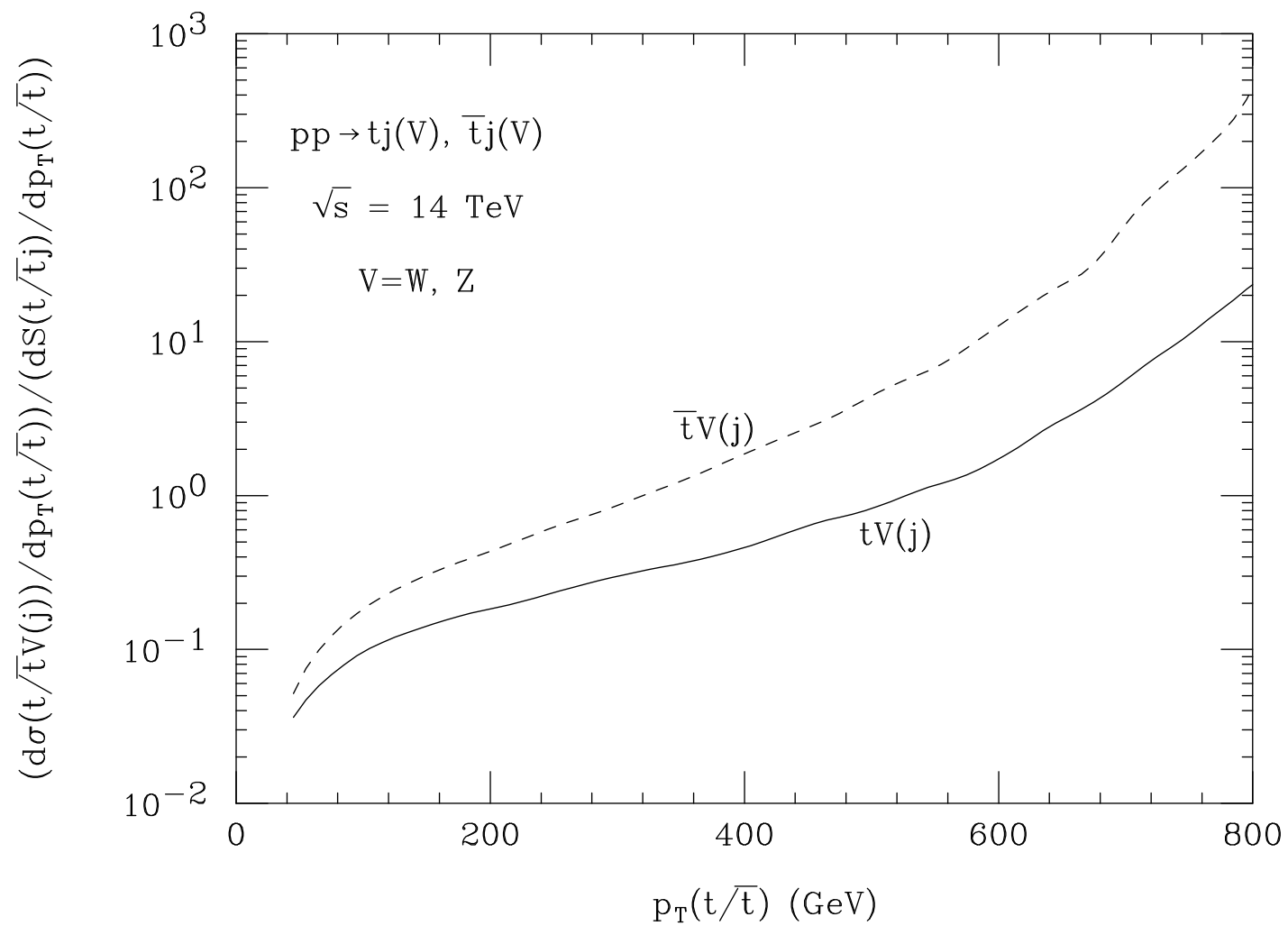
- one  $b$ -jet with  $p_T(b) > 35 \text{ GeV}$ ,  $|\eta(b)| < 2.5$ , additional  $b$ -jets in this region are vetoed

- one non-tagged jet with  $p_T(j) > 40 \text{ GeV}$ ,  $2.5 < |\eta(j)| < 4.5$  (forward tagging jet), additional jets are vetoed

- ☞ no  $b$ -tagging efficiencies are included in numerical results

- weak boson emission processes in  $t$ -channel single top production:  
 $pp \rightarrow tjV$
- $tjW$  occurs at  $\mathcal{O}(\alpha_s \alpha^2)$  (eg  $bg \rightarrow tWg$ );  $tjZ$  at  $\mathcal{O}(\alpha^3)$
- So, is  $\sigma(tjW) \gg \sigma(tj)$ ? Not necessarily.....
  - 👉 the jet veto suppresses  $tjW$  and  $tjZ$  production
  - 👉 **on the other hand**: at large  $p_T(t)$ , the forward jet requirement makes the  $tj$  cross section decrease much faster than the  $tjV$  rate
  - 👉 include contribution where jet from  $V$  decay is the one detected
    - ➔ need  $tW$  production at NLO QCD
  - 👉 use NLO  $tW$  production from MCFM (**Campbell, Tramontano**); rescale for  $W \rightarrow jj$ 
    - ➔ ignore QCD corrections to  $W$  decay in  $tW$  production
  - 👉 also include  $\bar{t}t \rightarrow tbW$  where  $b$ -quark is misidentified as light jet







- virtual weak corrections (Beccaria et al) are only known as a function of  $\sqrt{\hat{s}}$ 
  - direct comparison is impossible
- At  $\sqrt{\hat{s}} = 1$  TeV they reduce the cross section by  $\approx 20 - 30\%$ 
  - ☞  $\sqrt{\hat{s}} = 1$  TeV corresponds to roughly  $p_T(t) \sim 500$  GeV
  - ☞ at  $p_T(t) = 500$  GeV the  $tjV$  ( $\bar{t}jV$ ) to  $tj$  ( $\bar{t}j$ ) cross section ratio is 0.8 (4.4)
  - ☞ despite the jet veto, weak boson emission plays an important role in  $t$ -channel single top production at high energies

## 6 – Conclusions

- The size of the EW radiative corrections at hadron colliders depends on the experimental selection criteria
- In (partially) inclusive reactions, real EW radiative corrections may significantly reduce the effect of the  $\mathcal{O}(\alpha)$  one-loop corrections
- Details depend on the process considered, and the distribution which is studied.